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Greenhouse Gas Emissions from Beef Feedlot Surface Materials as Affected by Diet, Moisture, Temperature, and Time

Bryan L. Woodbury
USDA-ARS, bryan.woodbury@ars.usda.gov

John E. Gilley
University of Nebraska-Lincoln, john.gilley@ars.usda.gov

David B. Parker
USDA-ARS, david.parker@ars.usda.gov

Bobbi S. Stomer
USDA-ARS, Bobbi.Stomer@ars.usda.gov

GREENHOUSE GAS EMISSIONS FROM BEEF FEEDLOT SURFACE MATERIALS AS AFFECTED BY DIET, MOISTURE, TEMPERATURE, AND TIME

B. L. Woodbury, J. E. Gilley, D. B. Parker, B. S. Stromer

ABSTRACT. *A laboratory study was conducted to measure the effects of diet, moisture, temperature, and time on greenhouse gas (GHG) emissions from feedlot surface materials (FSM). The FSM were collected from open-lot pens where beef cattle were fed either a dry-rolled corn (DRC) diet containing no wet distillers grains with solubles (WDGS) or a DRC diet containing 35% WDGS. The FSM were collected, air-dried or mixed with 3.0 L of water to represent dry or wet conditions, and then incubated at temperatures of 5°C, 15°C, 25°C, or 35°C. Static flux chambers were used to quantify GHG emissions over a 14-day period. Flux data for each diet × moisture combination were analyzed using repeated measures in time. The largest GHG emissions occurred under wet conditions at temperatures of 25°C and 35°C. Flux values for these conditions typically were significantly greater than measurements obtained on the same day at 5°C and 15°C. Mean emissions under wet conditions for CO_2, CH_4, and N_2O were 35, 121, and 278 times greater, respectively, than emissions from dry FSM. The 0% WDGS diet produced mean CO_2 and N_2O flux measurements that were 1.8 and 1.5 times greater, respectively, than those obtained for the 35% WDGS diet. The 35% WDGS diet, in contrast, produced a mean CH_4 emission rate that was 6 times greater than the 0% WDGS diet. Management for GHG mitigation should include design and/or maintenance of pen drainage to speed drying as well as the use of modified animal diets.*

Keywords. *Air quality, Carbon dioxide, Confined animal feeding operations, Drainage, Emission rates, Feedlot, Greenhouse gas, Methane, Nitrous oxide, Pen design.*

Confined animal feeding operations (CAFOs) are used because of their increased efficiency and ability to better manage and care for beef cattle. This type of large-scale animal production facility creates atypical stresses on the surrounding environment that need be addressed to minimize potential impacts. Fortunately, this type of large-scale animal production operation offers greater opportunity for cost-effective environmental mitigation measures than more diffuse, smaller systems.

One of the concerns associated with CAFOs is greenhouse gas (GHG) emissions from pen surfaces (Garnett, 2009; Skinner et al., 2014; Misselbrook et al., 2016; Parker et al., 2017b). These GHGs include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). GHG emissions are driven by environmental conditions and management decisions, such as animal diet. For example, the total nitrogen in the diet retained by the animal and animal products is estimated to be only 5% to 20%; the rest is excreted in manure or urine (Mosier et al., 1998).

Beef cattle diets have changed considerably over the last couple of decades as diets have incorporated the use of wet distiller's grains with solubles (WDGS) (Spiehs et al., 2002). The inclusion of by-products from the ethanol industry in the feed for beef cattle has modified manure characteristics (Gralapp et al., 2002; Varel et al., 2008, 2010). Spiehs and Varel (2009) found that increasing the amount of WDGS in beef cattle rations increased phosphorus (P), nitrogen (N), and sulfur (S) intake and excretion. As a result, the animal diet can impact emission characteristics from pen surfaces where manure accumulates.

Production of GHGs has become a concern due to their potential impacts on the environment. Carbon dioxide from feedlot pen surfaces results primarily from microbial activity and the aerobic metabolization of carbonaceous manure that has accumulated on the pen surface. A 600 kg beef feedlot animal produces between 1200 and 1800 kg of manure solids each year (Eghball and Power, 1994). This equates to approximately 1.3 to 2.6 kg of carbonaceous material per animal each day (Kissinger et al., 2007).

Methane is also produced during microbial degradation of manure under anaerobic conditions with low redox potential (Saggar et al., 2004). An important characteristic of CH_4 is that it has a 100-year global warming potential (GWP) of

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The authors are **Bryan L. Woodbury,** Research Agricultural Engineer, USDA-ARS U.S. Meat Animal Research Center, Clay Center, Nebraska; **John E. Gilley,** Research Agricultural Engineer, USDA-ARS Agroecosystem Management Research Unit, Lincoln, Nebraska; **David B. Parker,** Research Agricultural Engineer, USDA-ARS Livestock Nutrient Management Research Unit, Bushland, Texas; **Bobbi Stromer,** Research Associate, USDA-ARS U.S. Meat Animal Research Center, Clay Center, Nebraska. **Corresponding author:** Bryan L. Woodbury, U.S. Meat Animal Research Center, P.O. Box 166, Clay Center, NE 68933; phone: 402-762-4275; e-mail: bryan.woodbury@ars.usda.gov.

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23 (IPCC, 2007). Methane production from manure has been observed to have strong temperature dependence (Jarvis et al., 1995). Gonzalez-Avalos and Ruiz-Suarez (2001) suggested that temperature plays the greatest role in controlling emissions within the same production system.

Nitrous oxide is formed during the transformation of nitrogen in the manure. Very small amounts of N_2O are found in the atmosphere (approx. 330 ppb), but N_2O has a GWP of 296, which is greater than both CO_2 and CH_4 (IPCC, 2007). The impact of nitrous oxide emissions from beef feedlots may be very important with the inclusion of WDGS in animal diets. Numerous researchers have shown that the excreted nitrogen content increases with increasing amounts of WDGS and crude protein in animal diets (Cole et al., 2005; Varel et al., 2008, 2010; Spiehs and Varel, 2009; Hales et al., 2015).

Nitrous oxide can be produced by both denitrifying and nitrifying microorganisms (Lipschultz et al., 1981; Schmidt and Belser, 1994; Tiedje, 1994, Stark and Firestone, 1995; Saggar et al., 2004). Nitrifying microbes convert soil NH_4 to NO_3 under aerobic conditions. Incomplete conversion can also result in the formation of N_2O (de Klein et al., 2003). Denitrification occurs only under anaerobic or anoxic conditions (Saggar et al., 2004; Uchida et al., 2008). Nitrous oxide is the gaseous intermediate of selected reaction sequences, which leaks from microbial cells into the soil environment (Mosier et al., 1998).

Precipitation and temperature may also influence emission types and amounts for a given diet. The influence of temperature on emissions is intuitive and has been well documented. However, the combined effects of diet, moisture, temperature, and time on the types of GHGs that are emitted are not well known. Commercial-sized feedlot pens have designs and slopes that can influence the areas where manure and moisture accumulate on the pen surface. Manure typically accumulates in greater quantities near the feed bunk apron and water trough (Woodbury et al., 2015). The base of the mounds may have a relatively large manure content and greater mixing with soil. Lower elevations within the pen may have substantial manure accumulations due to detachment and transport by drainage and overland flow during precipitation events. All of these physical characteristics could have significant impacts on GHG emissions.

Surface amendments have been investigated for controlling gas emissions from feedlot surfaces. Aguilar et al. (2014a) investigated the use of biochar from various feedstock sources for controlling GHG emissions from beef cattle feedlots. They did not find any significant differences in GHG emissions among the amendments during the first eight days after application. However, at days 10 and 15, the biochar materials performed significantly better than the control (i.e., no surface amendment) in reducing N_2O and CH_4 emissions.

Varel and Wells (2007) examined the use of the plant oil extract thymol in reducing odor and methane emissions from swine manure pits. They found that additions of 1.5 and 3.0 g L^{-1} of thymol reduced total gas production by 65% and 76%, respectively. Additionally, these thymol rates reduced methane production by 78% and 93%, respectively, for the 18 days of the study. Although there appears to be some promise of using surface additives to mitigate GHG emissions, they are limited by expense and the need to reapply to extend control. Pen design and/or management practices that reduce GHG emissions may be more cost-effective and could potentially be used in conjunction with surface additives to effectively control GHG emissions from pen surfaces.

The objective of this study was to determine the effects of diet, moisture, temperature, and time on the types and relative amounts of GHG emissions from feedlot surface materials (FSM). Although laboratory studies do not precisely represent field conditions, the information obtained from this investigation will serve to (1) identify pen designs or control practices available to feedlot managers for mitigating GHG emissions, and (2) provide the groundwork for future *in situ* studies to evaluate spatially selected mitigation practices for limiting GHG emissions from pen surfaces.

MATERIALS AND METHODS

COLLECTION OF FEEDLOT MATERIALS

Unconsolidated FSM were collected from six adjacent feedlot pens located at the U.S. Meat Animal Research Center (MARC) near Clay Center, Nebraska. The U.S. MARC feedlot is an open-air, earthen feedlot. Each 30 m × 90 m pen contained a central mound constructed from manure and soil, with a 3 m concrete apron located behind each feed bunk. Each pen had a slope gradient that ranged from 2% to 4% and was stocked with approximately 80 bullocks (steers). The cattle were fed dry rolled corn (DRC) diets containing either 0% or 35% WDGS (table 1). The bullocks entered the pens at 375 kg and were removed approximately 120 days later at 580 kg. Typical pen maintenance involves reshaping the mound and removing accumulated manure when the animals are marketed at the end of the feeding cycle. Generally, this takes place twice a year.

The FSM from three pens where cattle were fed each diet were collected during July using a skid-steer front-end

Table 1. Ingredient and nutrient composition (dry matter basis) of feedlot diets containing 0% (control) or 35% corn wet distillers grains with solubles (WDGS) fed during the finishing period.

Ingredient	Control	WDGS
Corn, dry rolled (%)	82.7	50.4
Corn, high moisture (%)	0.0	0.0
Corn WDGS (%)[a]	0.0	35.0
Corn silage (%)	12.8	13.5
Urea (%)	4.5	0.0
Alfalfa hay (%)	0.0	0.0
Mineral supplement (%)[b]	0.0	1.1
Composition, analyzed[c]		
Dry matter (%)	70.9	47.5
Crude protein (%)	12.8	16.8
Metabolizable energy (Mcal kg^{-1})	3.03	3.11
Phosphorus (%)	0.36	0.52
Calcium (%)	0.56	1.01

[a] Corn WDGS obtained from Abengoa Bioenergy Corp., York, Nebraska. Nutrient analysis was 31.3% DM, 31.6% CP, 13.7% oil, 0.83% P, and 0.73% S (DM basis).

[b] The supplement contained 94.45% limestone, 0.73% vitamins A, D, and E, and 2.742% Rumensin 80 (Elanco Animal Health, Indianapolis, Ind.), and 2.073% thiamine.

[c] Random samples were analyzed for nutrient composition throughout the study and were found to be within 5% of the calculated nutrient analysis.

loader. The material from each pen was placed in a low-profile pile near the pens and then thoroughly mixed. The manure was allowed to air-dry outdoors for approximately three weeks until it could be ground using a portable wood chipper to provide a homogenous material representing each diet for the laboratory study (Woodbury et al., 2015). The piles were not exposed to any appreciable rainfall during the drying period. The ground manure, which had an air-dried gravimetric moisture content of approximately 12%, was then stored indoors in separate 125 L plastic containers. This 12% antecedent moisture content was termed "dry" for the remainder of this study.

Experimental Procedures

The experimental treatments included diet (0% or 35% WDGS), moisture condition, i.e., dry (no water added) or wet (total of 3.0 L added), temperature (5°C, 15°C, 25°C, or 35°C), and time following initial placement within a temperature and humidity-controlled environmental chamber (0, 2, 4, 7, 9, 11, or 14 days). Each of the experimental treatments was replicated four times, for a total of 448 data points (2 diets × 2 moisture conditions × 4 temperatures × 7 days × 4 replications). The relative humidity within the environmental chamber was maintained between 50% and 55% by a sensor that was connected to a controller that turned on/off a humidifier or de-humidifier as needed.

The experimental procedures for repacking the FSM into stainless steel pans were reported by Woodbury et al. (2015). Approximately 6.0 kg of FSM (dry weight) from each pen was mixed with distilled water for the wet experimental treatment. A total water addition of 3 L was selected to represent a 20 mm rainfall event. Total water additions were adjusted slightly to account for the antecedent moisture content (12%) of the FSM. The dry treatment had no water added. The FSM were placed and initially packed by hand within stainless steel pans (500 m long × 300 m wide × 65 mm deep) and then pressed into a uniform depth of 60 mm using a hydraulic press to obtain a consistent density of 615 kg m^{-3} among the treatments. Total pan weights were recorded after compaction to the specified volume. Water was added daily to the wet FSM treatment using a hand sprayer to compensate for evaporated water. Constant water content was maintained to represent an extended wet period that sometimes occurs on feedlot pen surfaces. Pans were randomized on three identical racks located in the environmental chamber. Air samples for measurement of GHGs were collected 0, 2, 4, 7, 9, 11, and 14 days following treatment preparation. The air samples were obtained for a specified temperature, and then the material was discarded. The pans were then repacked with new manure, and the temperature of the chamber was adjusted for additional collection of GHGs.

Static Chamber Flux Measurements

The fluxes of CO_2, CH_4, and N_2O were measured using static vented chamber specifications developed for the USDA-ARS's GRACEnet project (Parkin and Venterea, 2010). A stainless steel vented chamber cover with dimensions of 500 mm long × 300 mm wide × 100 mm deep was fitted directly over the pans containing packed feedlot surface material. The cover was sealed using a rubber gasket and clamps to ensure an airtight closure during the flux measurement phase. Gas samples were collected from the headspace over a 30 min sampling period at 0, 10, 20, and 30 min. Prior to headspace sampling at the specified times, a 20 mL sample from the headspace sampling port was taken and discharged to the atmosphere to prepare the sample tubing for repetitive gas collection. After preparing the sample port tubing, a 30 mL sample was obtained using a syringe. The syringe with the sample gas was fixed with a needle, and 5 mL of sample gas was discharged to purge the needle and eliminate the unneeded sample volume. The remaining 25 mL of sample gas was then placed in a 12 mL evacuated glass sample tube sealed with a septum.

Prior to sample collection, the 12 mL glass sample tubes were evacuated to an absolute pressure of 150 Pa. The samples were analyzed for CH_4, CO_2, and N_2O within 24 h of sampling using a gas chromatograph (8610C, SRI Instruments, Menlo Park, Cal.). A calibration curve was generated at the beginning and end of each sample run. Calibration standards were also periodically analyzed during the experiment to verify that there was no calibration drift.

Statistical Analysis

For each combination of diet and moisture, the flux data were analyzed as a completely randomized design with repeated measures in time using the SAS Mixed procedure (SAS, 2011). For each analysis, fixed effects were temperature, diet, time, and temperature × time interaction. Diet × temperature was the subject of the repeated measures. Several covariance structures were tested, and the covariance structure resulting in the smallest Akaike and Schwarz Bayesian criteria was used in each analysis. The heterogeneous autoregressive covariance structure (ARH(1)) was used in all but one of the analyses, in which case the autoregressive structure (AR(1)) was used. Because significant ($p \leq 0.05$) temperature × time interactions were detected using the single-degree-of-freedom F-tests, pairwise comparisons of the simple-effects means were conducted within the PDIFF option of SAS.

Results and Discussion

The following discussion primarily focuses on CO_2, CH_4, and N_2O fluxes for the wet treatments. Even though temperature differences for the dry treatment for a given animal diet and gas emission were measured, the gas emissions from the wet FSM were 35 to nearly 300 times greater. As a result, the emissions from the dry moisture treatments were minor and are not highlighted below.

Carbon Dioxide

The mean CO_2 flux of 214.3 g m^{-2} d^{-1} measured for the 0% WDGS diet was nearly twice the 116.5 g m^{-2} d^{-1} obtained for the 35% WDGS diet (table 2). The CO_2 flux of 321.8 g m^{-2} d^{-1} measured for the wet FSM was 35 times greater than the 9.1 g m^{-2} d^{-1} obtained under dry conditions.

Table 2. Greenhouse gas emissions as affected by diet, moisture, and temperature. Values for each variable are averaged across treatments. Numbers in parentheses are standard deviations of means.

	Carbon Dioxide ($g\ m^{-2}\ d^{-1}$)	Methane ($g\ m^{-2}\ d^{-1}$)	Nitrous Oxide ($g\ m^{-2}\ d^{-1}$)
Diet (WDGS)[a]			
0%	214.3 (311.1)	0.052 (0.135)	0.674 (0.135)
35%	116.5 (151.7)	0.316 (0.850)	0.445 (0.895)
Moisture			
Dry	9.1 (10.6)	0.003 (0.007)	0.004 (0.011)
Wet	321.8 (274.9)	0.364 (0.842)	1.11 (1.25)
Temperature			
5°C	38.0 (37.2)	0.004 (0.005)	0.170 (0.603)
15°C	122.4 (138.2)	0.013 (0.023)	0212 (0.508)
25°C	229.1 (266.4)	0.146 (0.274)	0.859 (1.226)
35°C	272.1 (352.4)	0.572 (1.123)	0.995 (1.29)

[a] WDGS = wet distillers grains with solubles.

Aguilar et al. (2014a) evaluated the effects of water application on GHG emissions from FSM. They collected FSM from multiple pens on two commercial feedlots in Kansas, air-dried the material to 0.10 g/g water content, and then sieved the FSM to remove any material larger than 4.75 mm in diameter. They then placed approximately 218 g of the prepared FSM in a 1 L glass container and simulated a 16.7 mm intense rain event by adding 111 g of water. The containers were incubated at room temperature for approximately 30 days. The CO_2 flux values that Aguilar et al. (2014a) reported for moist/loose packed and moist/compacted FSM were similar to our wet FSM CO_2 flux measurements. However, our dry FSM CO_2 flux values were approximately 10 times greater than what Aguilar et al. (2014a) reported. There are several differences (i.e., air dry moisture, animal diet, incubation temperature., soil type, etc.) between the two experimental designs that may explain the differences in dry CO_2 flux rates; however, it is important to note that both studies demonstrate that comparatively little CO_2 is emitted when FSM is dry.

Carbon dioxide flux over the 14-day period increased linearly with temperature, varying from 38.0 to 272.1 $g\ m^{-2}\ d^{-1}$ as the temperature increased from 5°C to 35°C (fig. 1a). A linear regression equation was derived relating CO_2 flux rates (y) in $g\ m^{-2}\ d^{-1}$ to temperature (x) in °C:

$$y = 8.09x + 3.60\ (R^2 = 0.976) \quad (1)$$

When the data were sorted to show the impact of diet on flux rates, the slope (11.4) of the regression equation for the 0% WDGS diet was more than twice that of the 35% WDGS diet (4.36) (figs. 1b and 1c). These results indicate that the types of microbial metabolisms that generate CO_2 were much greater for 0% WDGS than for 35% WDGS (Varel et al., 2008, 2010).

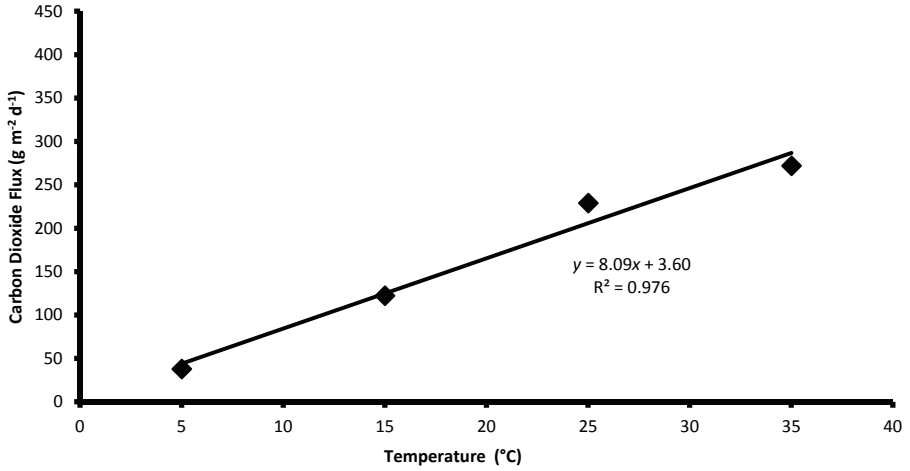
Carbon dioxide flux rates were substantially greater for wet FSM conditions (table 2). The largest flux values occurred under wet conditions for the 0% WDGS diet (fig. 2a). The 0% WDGS flux rates at both 25°C and 35°C where nearly twice those obtained on the same sample day for the 35% WDGS treatment (figs. 2a and 2b). By day 7, there were no significant differences measured between the 25°C and 35°C temperatures (fig. 2a). The 15°C temperature did not peak like the 25°C and 35°C temperatures but steadily climbed until day 14. By day 14, only the 5°C temperature was significantly different from the other temperature treatments. The emission pattern for 35% WDGS was similar to the 0% treatment, although much less in magnitude. By day 11, the only temperature that was different for 35% WDGS was 5°C (fig. 2b).

The CO_2 flux rate is a general indicator of microbial activity. Although manure constituent metabolism was not measured during this study, other researchers have investigated the hierarchy of manure substrate metabolism. Generally, manure constituents are consumed due to the ease with which organisms can metabolize the substrate and the energy available to the organism for growth (Mackie et al., 1998; Miller and Varel, 2001, 2002; Miller and Berry, 2005). Miller and Varel (2002) observed a hierarchy of substrate utilization during manure slurry incubations. They concluded that starch was the dominant substrate lost during incubations and that protein fermentation occurred only in the absence of starch. WDGS is the result of a fermentation process designed to convert corn starch to ethanol for use as a transportation fuel additive. Due to this process, the 35% WDGS diet did not contain as much starch, but most of the other feed constituents, including proteins, were conserved. Therefore, when WDGS is fed to animals to meet their energy needs, the protein in the diets are in excess when compared to a traditional corn-based diet with 0% WDGS. When water was added to the FSM in this study, the microorganisms increased in activity, but the increase for the 35% WDGS diet was much less than for the 0% WDGS diet, most likely due to the energetics of the manure constituents.

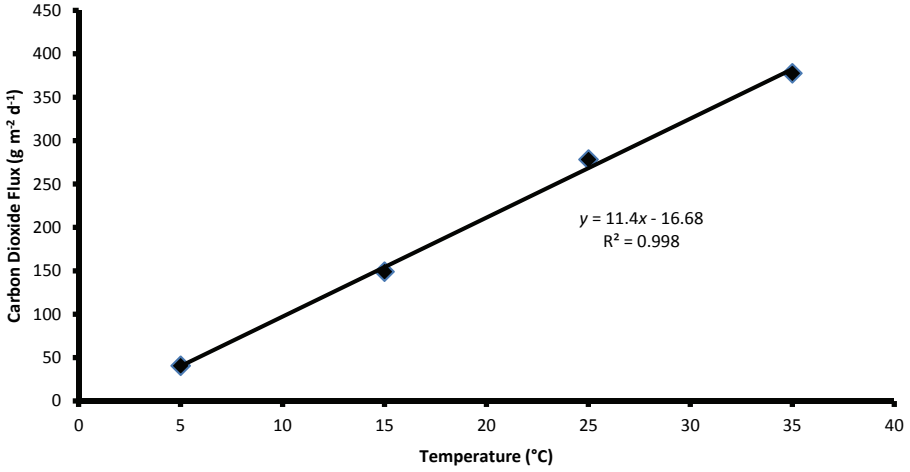
METHANE

The CH_4 flux of 0.316 $g\ m^{-2}\ d^{-1}$ measured for the diet containing 35% WDGS was six times greater than the 0.052 $g\ m^{-2}\ d^{-1}$ obtained for the 0% WDGS diet (table 2). The CH_4 and CO_2 emission patterns differed because a greater CH_4 flux rate occurred for 35% WDGS than for 0% WDGS. The flux rate of 0.364 $g\ m^{-2}\ d^{-1}$ measured for the wet FSM was 121 times greater than the 0.003 $g\ m^{-2}\ d^{-1}$ obtained under dry conditions.

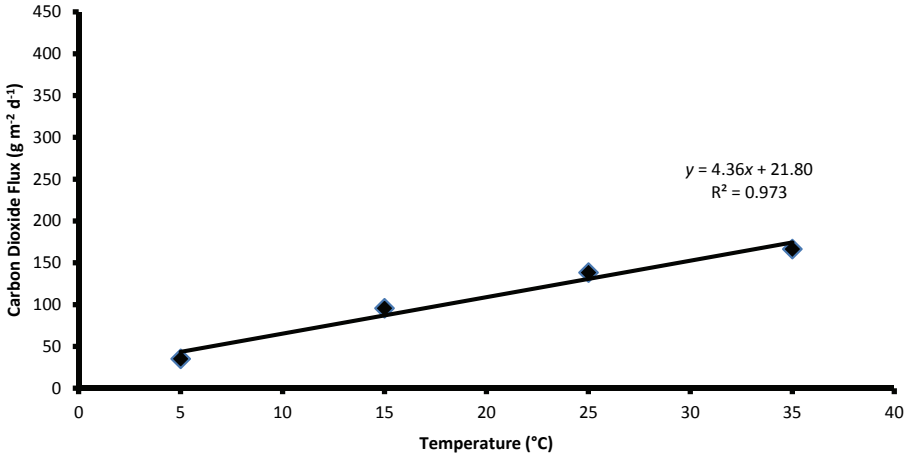
Our wet CH_4 flux rates were approximately 10 times greater than those estimated by Aguilar et al. (2014a), but our dry CH_4 flux was very similar. Part of the difference could be explained by our experimental design. We investigated temperature variation ranging from 5°C to 35°C. In addition, we did not exclude large clods, which might contain more organic material. Methane generation in soils is driven by many environmental factors that can vary spatially and temporally within feedlot pens (Le Mer and Roger, 2001; Weiland, 2010). An additional difference that can substantially affect CH_4 generation is the impact of excreted antibiotics on the methanogenesis process (Lallai et al., 2002; Stone et al., 2009). The feedlot at the U.S. MARC is commercially sized; however, it is primarily used for large-scale animal production research, which results in different management of the animals and pen facilities when compared to commercial feedlots. Although differences in CH_4 flux from feedlot pen surfaces have been reported among various laboratory and *in situ* studies, a notable result from these studies is the near elimination of CH_4 emissions when the FSM is dry.



(a) Overall average



(b) 0% WDGS



(c) 35% WDGS

Figure 1. Impact of temperature on carbon dioxide flux emissions: (a) flux values for carbon dioxide as affected by temperature averaged over all other treatments, and (b and c) flux values for carbon dioxide as affected by diet and temperature averaged over all other treatments.

The mean CH_4 flux increased exponentially over the 14-day period, varying from 0.004 to 0.572 g m^{-2} d^{-1} as temperature increased from 5°C to 35°C (fig. 3a). A regression equation was derived relating the mean CH_4 flux rates (y) in g m^{-2} d^{-1} to temperature (x) in °C (fig. 3a):

$$y = 0.0014e^{0.174x} \quad (R^2 = 0.982) \qquad (2)$$

When the data were sorted to show the impact of diet on

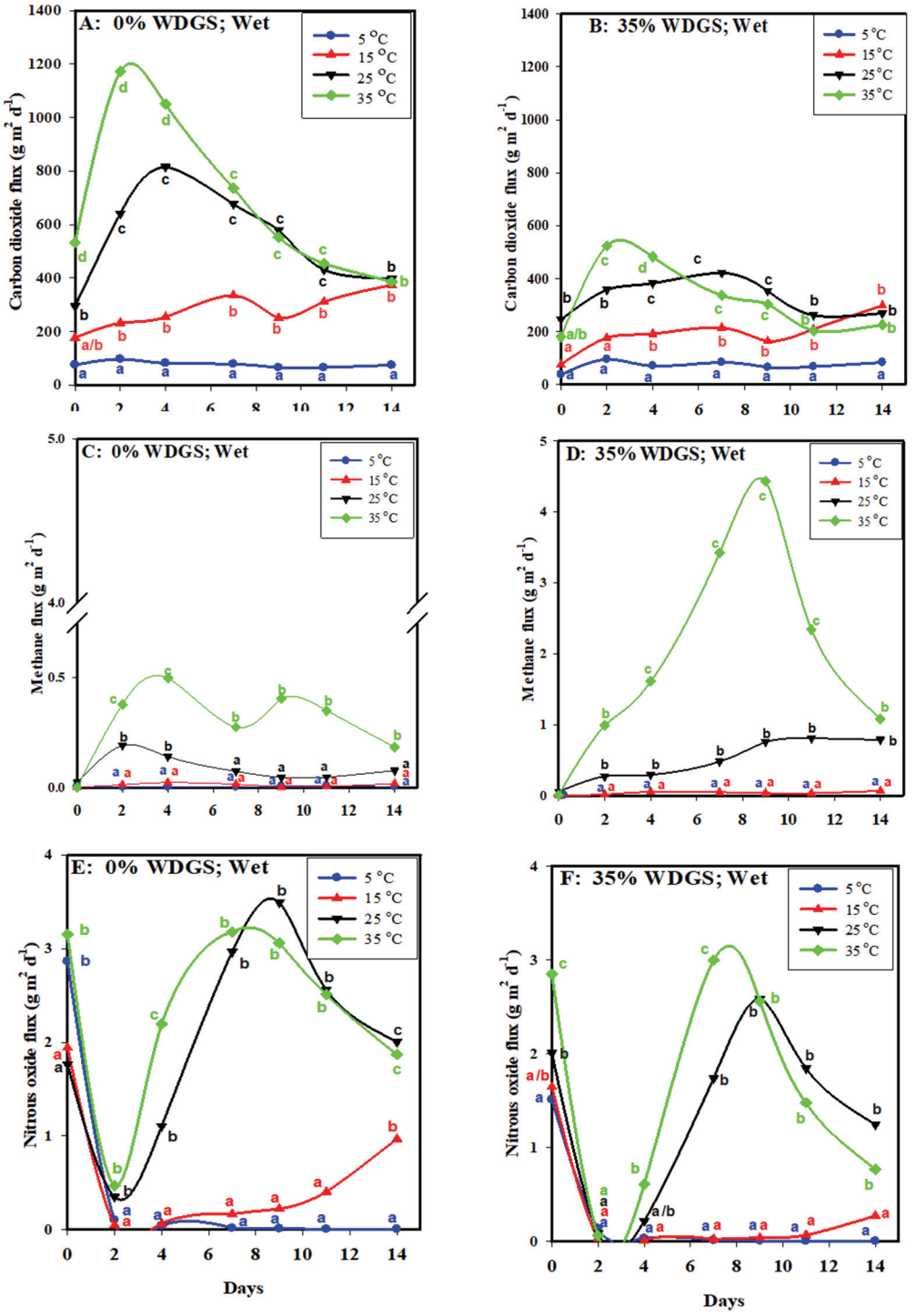
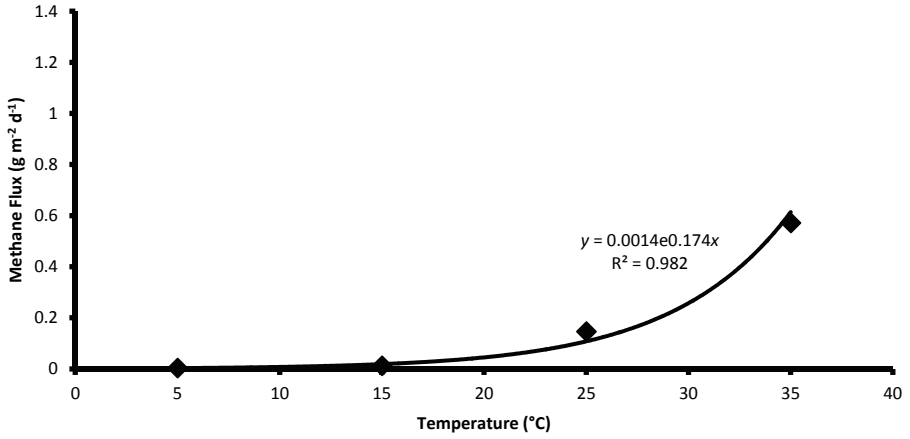


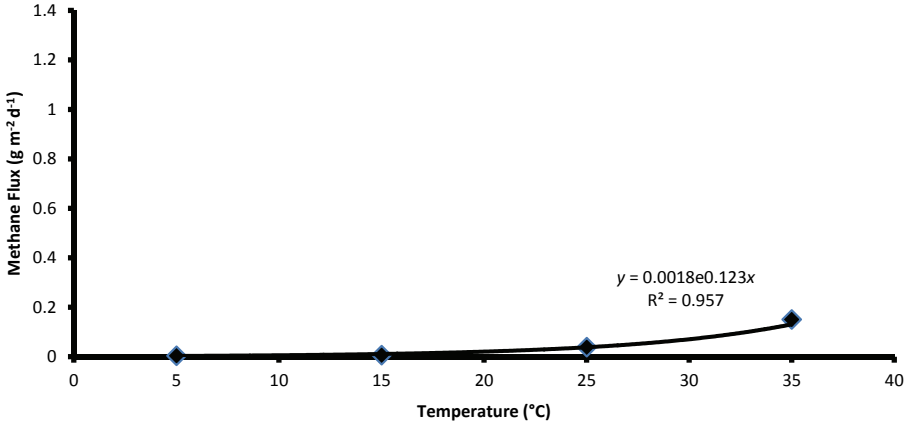
Figure 2. Emission fluxes for CO_2, CH_4, and N_2O for the 0% and 35% WDGS during the 14-day study period. Data were analyzed using repeated measures with sample day as the repeated measure. Different letters among the temperatures for a given diet and gas emission indicate differences at the $p \leq 0.05$ probability level.

CH_4 flux rates, the slope (0.123) of the regression equation for the 0% WDGS diet was less than the slope (0.196) for the 35% WDGS diet (figs. 3b and 3c).

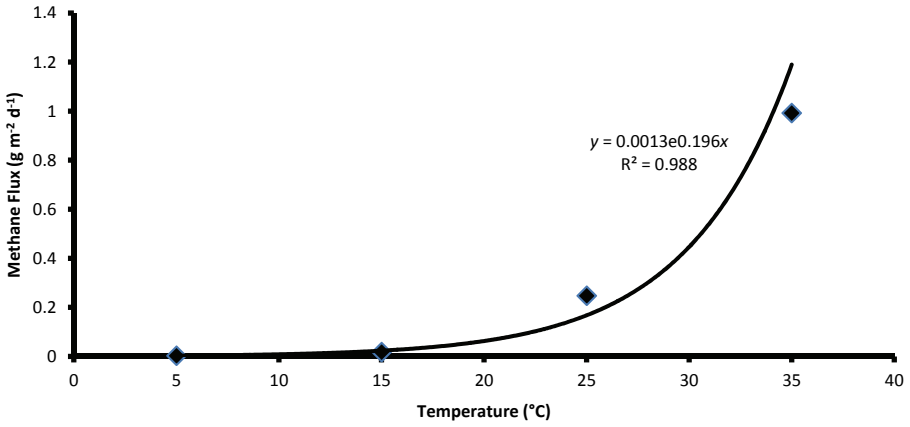
Methane flux rates were substantially larger under wet conditions over the 14-day period when compared to a dry environment (table 3). Under wet conditions for both diets, CH_4 emissions were minimal and showed little change with time at temperatures of 5°C and 15°C (figs. 2c and 2d). The largest CH_4 flux values occurred under wet conditions at a temperature of 35°C for the diet containing 35% WDGS (fig. 2d). Methane emission rates steadily increased to a maximum value of 4.4 g m^{-2} d^{-1} at nine days following the addition of water and then decreased to 1.1 g m^{-2} d^{-1} at 14 days (fig. 2d). At the 25°C temperature for 35% WDGS, the CH_4 flux steadily increased to approximately 0.8 g m^{-2} d^{-1} by day 9 and remained at that level through day 14



(a) Overall average



(b) 0% WDGS



(c) 35% WDGS

Figure 3. Impact of temperature on methane flux emissions: (a) flux values for methane as affected by temperature averaged over all treatments, and (b and c) flux values for methane as affected by diet and temperature averaged over all other treatments.

(fig. 2d). The CH_4 flux for 0% WDGS was below 0.2 g m^{-2} d^{-1} for all temperatures except 35°C (fig. 2c). When the temperature was increased to 35°C, the CH_4 flux increased significantly to approximately 0.5 g m^{-2} d^{-1} by day 2 and remained significantly different from the other three temperatures.

In contrast to corn, WDGS are high in protein, fiber, fat, P, and S but low in starch (Spiehs et al., 2002). Varel et al. (2008) found during incubation of beef cattle manure slurries that the L-lactate concentration contributed to lower slurry pH (6.3, 7.1, 7.6, and 8.2, respectively, for 0%, 20%, 40%, and 60% WDGS). They concluded that these low pH values inhibited microbial fermentation, *E. coli* persistence, and methane production. Because of the favorable pH in the 40% and 60% WDGS slurries, more methane was generated dur-

Table 3. Greenhouse gas emissions for each diet and temperature treatment for the study period. For a given GHG and diet, values in the same column (day) followed by different letters are statistically different at the p ≤ 0.05 level.

GHG	Diet	Temperature (°C)	Day 0	2	4	7	9	11	14
CO_2	0%	5	2.7 a	4.5 a	3.7 a	4.5 a	3.4 a	3.7 a	4.4 a
		15	3.5 a	6.2 a	**7.3 ab**	4.7 a	6.0 a	5.8 a	10.9 a
		25	5.5 a	**18.1 b**	**14.1 b**	**13.5 b**	**12.8 b**	8.6 a	6.9 a
		35	2.7 a	**15.1 b**	**10.2 ab**	**11.0 b**	6.5 a	7.0 a	3.5 a
	30%	5	2.8 a	6.3 a	4.9 a	5.5 a	4.5 a	4.6 a	4.4 a
		15	3.4 a	5.9 a	**8.7 ab**	**11.8 ab**	9.3 b	10.7 a	7.5 a
		25	7.4 a	**38.3 b**	**28.6 bc**	**18.9 ab**	19.9 c	12.8 a	10.5 a
		35	6.8 a	15.5 a	**18.5 c**	**13.8 b**	5.4 a	9.7 a	5.2 a
CH_4	0%	5	0.006 a	0.001 a	0.002 a	0.004 a	**0.006 b**	0.009 a	**0.009 b**
		15	0.003 a	0.001 a	0.004 a	0.004 a	**0.003 ab**	0.004 a	0.002 a
		25	0.005 a	**0.007 b**	0.003 a	0.006 a	0.002 a	0.005 a	0.002 a
		35	0.003 a	0.001 a	0.003 a	0.005 a	**0.005 ab**	0.003 a	0.002 a
	30%	5	0.002 a	0.002 a	**0.004 ab**	0.002 a	0.004 a	0.001 a	0.002 a
		15	0.002 a	0.001 a	0.001 a	0.002 a	0.001 a	0.003 a	0.001 a
		25	**0.008 b**	0.005 a	0.001 a	0.003 a	0.002 a	0.003 a	0.002 a
		35	**0.006 ab**	0.008 a	**0.009 b**	0.003 a	0.006 a	0.002 a	0.004 a
N_2O	0%	5	0.012 a	0.001 a	0.001 a	0.001 a	0.000 a	0.001 a	0.001 a
		15	0.002	0.000 a	0.000 a	0.015 a	0.001 a	0.001 a	0.001 a
		25	0.006 a	0.001 a	0.003 a	0.009 a	**0.008 ab**	**0.004 b**	**0.002 ab**
		35	0.009 a	0.001 a	**0.013 b**	0.011 a	**0.021 b**	**0.005 b**	**0.003 b**
	30%	5	0.004 a	0.001 a	0.001 a	0.001 a	0.001 a	0.001 a	0.001 a
		15	0.002 a	0.000 a	0.000 a	0.001 a	0.000 a	0.001 a	0.001 a
		25	0.001 a	0.001 a	0.002 a	**0.026 b**	**0.016 b**	0.003 b	0.002 a
		35	0.006 a	0.001 a	0.001 a	0.004 a	**0.006 ab**	0.003 ab	0.005 a

ing a 28-day static incubation. The moisture conditions used during this study simulated chronic wet periods and approached those found with beef cattle manure slurries.

NITROUS OXIDE

The N_2O flux rate of 0.674 g m^{-2} d^{-1} measured for the 0% WDGS diet was significantly greater than the 0.445 g m^{-2} d^{-1} obtained for the 35% WDGS diet (table 2). The flux of 1.11 g m^{-2} d^{-1} measured for the wet FSM was 277 times greater than the 0.004 g m^{-2} d^{-1} obtained for dry conditions (table 2).

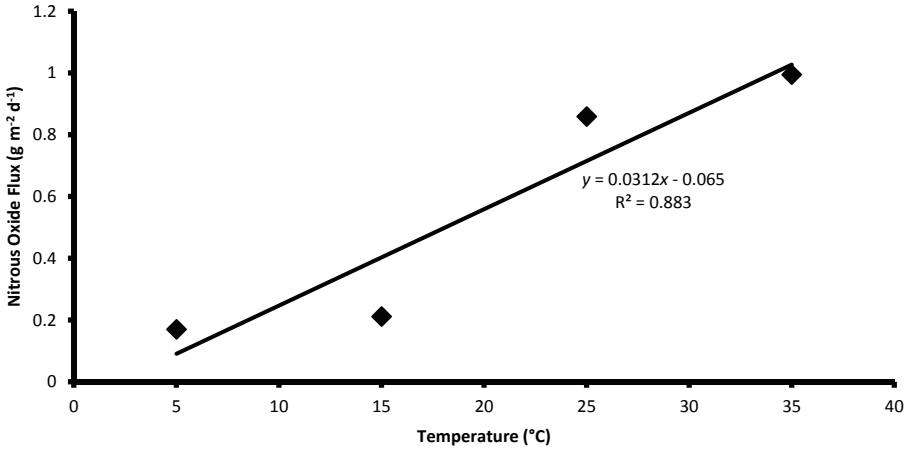
Recently, Parker et al. (2017a, 2017b) conducted studies to quantify N_2O emissions after a rainfall event on surface materials from simulated open-lot beef cattle pens. Their study used 1 m × 1 m × 0.89 m deep steel pans that were repacked with FSM collected from a commercial feedlot in Deaf Smith County, Texas. Single-application simulated rainfall amounts (6.3, 12.7, 25.4, and 50.8 mm) were applied, and N_2O emissions were monitored for 45 days. The researchers reported distinct episodes of N_2O emissions during the observation period. The first episode had a duration of only 10 h with a peak at 2 h after water addition. The N_2O emission during this period was 0.24 to 4.8 g m^{-2} d^{-1}. The second episode had a duration of 40 days with a peak at 15 days. The N_2O emission during this second period varied from 0.001 to 0.84 g m^{-2} d^{-1}. Parker et al. (2017b) estimated that the second peak accounted for 69% to 91% of the cumulative N_2O emission over the 45-day study. Aguilar et al. (2014a, 2014b) reported very similar emission rates for FSM that contained water amounts above typical air-dry moisture contents.

The mean N_2O flux rates increased over the 14-day period in a linear fashion with temperature, varying from 0.170 to 0.995 g m^{-2} d^{-1} as temperature increased from 5°C to 35°C (table 2). A regression equation was derived relating mean N_2O flux (y) in g m^{-2} d^{-1} to temperature (x) in °C (fig. 4a):

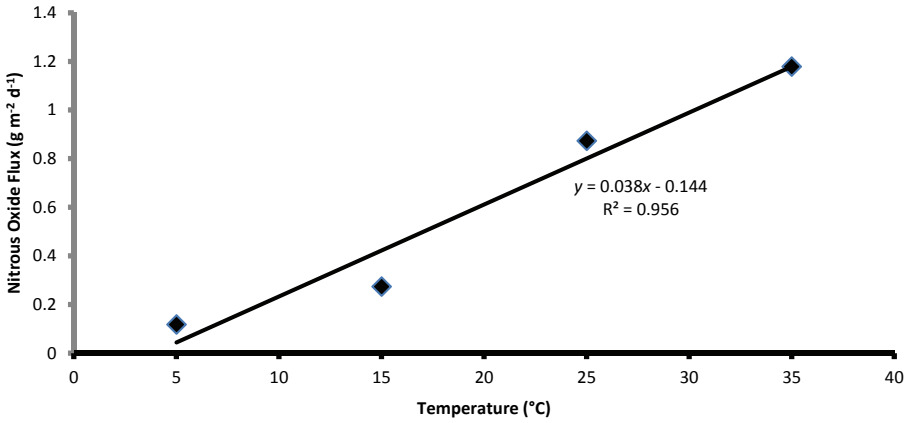
$$y = 0.0312x - 0.065 \ (R^2 = 0.883) \quad (3)$$

When the data were sorted to show the impact of diet on N_2O flux rates, the slope (0.038) of the regression equation for the 0% WDGS diet was slightly larger than the slope (0.025) for the 35% WDGS diet (figs. 4b and 4c).

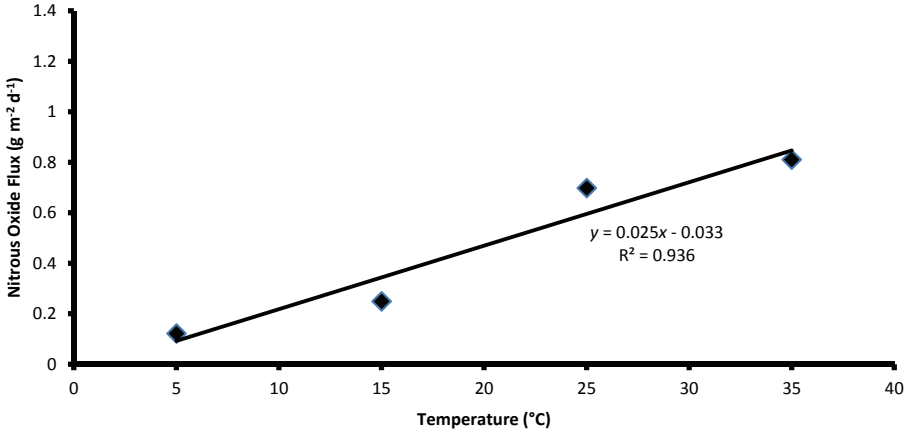
Nitrous oxide flux was substantially larger under wet conditions for both diets for the 14-day sample period (table 3, figs. 2e and 2f). Nitrous oxide flux rates were relatively small under dry FSM conditions. For both diets under wet conditions at temperatures of 5°C and 15°C, N_2O flux was at a maximum during the initial sampling date (figs. 2e and 2f). The N_2O flux then decreased to minimal values during the next four sampling periods and remained low until the end of the study. The initial N_2O flux for all diets and temperatures was probably due to the accumulation of nitrified ammonia created under the aerated conditions that existed during collection and storage of the dry FSM prior to wetting. Previous work has shown similar trends and the capacity of FSM to nitrify under aerated conditions (Woodbury et al., 2001). Parker et al. (2017b) speculated that the sharp decline in N_2O flux after the initial addition of water was not the exhaustive consumption of readily available nitrate-nitrogen but was possibly the result of a limiting enzyme necessary for nitrification and denitrification. Nielsen and Revsbeck (1998) investigated nitrogen transformations in aerobic soils receiving liquid cattle manure and duck litter. They found a tight coupling of nitrification and denitrification, which results in a complex synthesis of the enzymes necessary for each process. They also showed that a high rate of ammonium liberation from the manure seemed to inhibit nitrification. Tiedje (1994) detailed six different processes that reduce nitrate in the soil environment. Each of these processes is regulated by environmental conditions, including pH and O_2 content. Additionally, the pen surface and FSM may become a sink for the N_2O produced, thereby limiting



(a) Overall average



(b) 0% WDGS



(c) 35% WDGS

Figure 4. Impact of temperature on nitrous oxide flux emissions: (a) flux values for nitrous oxide as affected by temperature averaged over all treatments, and (b and c) the flux values for nitrous oxide as affected by diet and temperature averaged across all other treatment variables.

the amount measured as emissions (Chapuis-Lardy et al., 2007). In our study, the N_2O flux rates for wet conditions for both diets were also relatively large during the initial sampling date at temperatures of 25°C and 35°C and then decreased to minimal values for the next sampling period (figs. 2e and 2f). Nitrous oxide emissions increased substantially until day 7 before receding again until the end of the 14-day sampling period.

Aguilar et al. (2014a) saw two peak emissions for moist/loose manure material when compared to moist/compact manure material. They attributed the difference to the larger wet bulk density of the moist/compacted manure, which delayed gas diffusion from the substrate to the surface/air interface. In addition, the top layer of the moist/com-

pacted manure was able to quickly diffuse N_2O to the headspace, which can also explain the rapid and large N_2O flux decline during the first hour of the experiment. In our study, the dry bulk densities were uniform across all treatments; however, the surface/air interface was impacted by the daily wetting and drying cycle of the FSM surface. Water was added daily to maintain static water status throughout the study. At higher temperatures, the amount of water added increased to 500 to 600 mL per day. It was observed that most of the water evaporated in the first few hours after addition, and evaporation slowed substantially as a surface boundary condition developed. This periodic drying of the soil surface may have caused an aerobic/anoxic cycle to develop that would mineralize and nitrify ammonia under dry conditions and then denitrify nitrogen once water was added. Additional work is needed to verify this process.

Feedlot Management Considerations

Diet, temperature, moisture, and time are primary drivers of CO_2, CH_4, and N_2O flux rates. Little can be done to alter the frequency and duration of precipitation events on open-lot beef cattle pens. However, management options are available to alter the rate at which the pen surface dries following a precipitation event. These management controls include: (1) the amount of manure that is allowed to collect on the pen surface, (2) how well the drainage systems of the pens is maintained, and (3) how much soil is mixed with the manure on the pen surface.

Typically, only small amounts of manure are removed during the feeding cycle, and this removal is mainly associated with the areas of the pen where most of the manure accumulates. Manure is removed to improve the condition of the pen surface to maintain animal health and performance. More frequent manure removal during the feeding cycle is complicated by the animals housed in the pens and by the weather conditions, limiting the time when manure can be effectively removed. Additionally, animal traffic around the perimeter of the pen can cause manure and soil to be pushed up under the fence, inhibiting water from effectively draining from the pen.

Pen drainage is a crucial design element for open-lot, beef cattle feedlot pens. The design must effectively convey water from the pen surface to a runoff control structure. Most well-designed feedlots have an effective drainage system; however, drainage systems may be compromised by the accumulation of FSM at the pen drainage point due to animal traffic. Proper maintenance of drainage from the pen surface and the removal of accumulated manure could serve to maintain existing drainage patterns and allow the pen surface to dry more quickly following a precipitation event.

Earthen, open-lot feedlot pens contain a mixture of soil and manure, which creates large amounts of material that must be removed to adequately maintain pen drainage. Woodbury et al. (2013) evaluated the use of fly ash from a coal-fired power plant as an alternative to earthen pens. They found that the presence of fly ash within feedlot pens reduced the amount of material that needed to be removed during reconditioning of the pen surface following each feeding cycle. The amount of material removed was reduced by approximately 50% and the amount of fill material required was less than 75% of the amount required for earthen pen surfaces. Pens containing fly ash resulted in a surface that dried more quickly and allowed better removal of accumulated manure. Therefore, use of fly ash on feedlot pen surfaces could reduce GHG emissions.

Limitations of Laboratory Study

This study was conducted under laboratory conditions using unconsolidated materials collected from feedlot surfaces. The experimental treatments, which included diet, moisture, temperature, and time, could not have been easily reproduced within individual feedlot pens where cattle were present. In feedlot pens containing cattle, other variables not examined in this study, including varying climatic conditions, surface disturbance by cattle hooves, and the input of recently deposited manure, would be expected to influence VOC emissions. However, information obtained from this study can be used to identify pen designs or control practices for mitigating GHG emissions and provide the groundwork for future *in situ* investigations.

Conclusions

A laboratory study was conducted to measure the effects of diet, moisture, temperature, and time on emissions of GHG from FSM. The largest GHG emissions occurred under wet conditions at temperatures of 25°C and 35°C. Flux values measured under wet conditions at temperatures of 25°C and 35°C varied with time but typically were significantly greater than the emissions obtained at 5°C and 15°C on the same day. The peak CO_2 emission occurred two to four days following the start of the simulated wet period. Similarly, the peak emission of CH_4 occurred at approximately seven to nine days. The largest N_2O flux rates were measured immediately following the simulated rainfall event and had a secondary peak at seven to nine days.

The traditional corn diet produced mean CO_2 and N_2O flux measurements that were 1.8 and 1.5 times greater, respectively, than those obtained for the diet containing 35% WDGS. The diet with 35% WDGS, in contrast, produced an overall CH_4 emission rate that was 6 times greater than that measured for the 0% WDGS diet. The mean flux values for dry conditions were negligible compared to the wet FSM. The mean flux values obtained under wet conditions for CO_2, CH_4, and N_2O were 35, 121, and 278 times greater, respectively, than the mean values measured for dry conditions.

Temperature affected CO_2 and N_2O flux measurements, with flux rates increasing linearly with temperature. By comparison, methane production increased exponentially with temperature. The CO_2 flux for the 0% WDGS diet was twice that of the 35% WDGS diet. In contrast, the 35% WDGS diet generated greater amounts of methane than the 0% WDGS diet.

Management of feedlot pen surfaces for reduction of GHG emissions can present difficult challenges for operators. This laboratory study illustrates that GHG emissions from FSM are significantly affected by diet, moisture, temperature, and time. Understanding the critical factors that in-

fluence GHG emissions is important for the development of effective mitigation practices. This laboratory study illustrates the need for an effective pen drainage system and its proper maintenance. In addition, a better pen surface using alternative materials, such as fly ash, should be investigated to improve surface drying following precipitation events. Based on the results from this investigation, *in situ* studies can be conducted to develop targeted management practices for reducing GHG emissions by modifying pen drainage designs and animal diets.

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NOMENCLATURE

CAFOs = confined animal feeding operations
DRC = dry rolled corn
FSM = feedlot surface materials
GHG = greenhouse gas
GWP = global warming potential
WDGS = wet distillers grains with solubles.

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